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Flow Visualization and Measurement of a Synthetic Jet Actuator Performance Using PIV System

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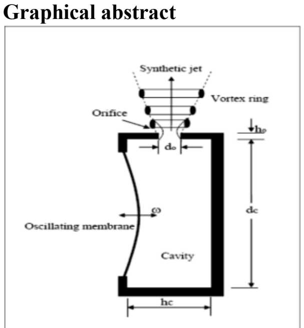
Graphical abstract



Abstract

This paper presents the performance of a piezoelectric Synthetic Jet Actuator (SJA) in quiescent flow. Pulse jet velocity and vorticity were taken as the parameter to evaluate the performance of SJA. PIV measurements on the jet flow at the orifice exit of a round SJA were conducted by varying the oscillating in frequency and voltage. The location of 5mm above orifice was identified as the optimum location for maximum pulse jet measurements. The maximum pulse jet velocity and vorticity obtained were 18.77 m/s and 242.5s^{-1}. The PIV experiment showed that by varying oscillating frequency at fixed input voltage, the performance of SJA was greatly affected by Helmholtz resonance. While in the investigation of varying input voltage at fixed oscillating frequency, diaphragm defection was the parameter that affects the performance of the SJA. Besides, PIV measurement showed that the flow patterns of vortex structure formation were affected by the oscillating frequency and pulse jet velocity.

Keywords: Quiescent flow, synthetic jet actuator, piezoelectric diaphragm, PIV

NOMENCLATURE

Δ	= Diaphragm's Displacement, *m*
A	= Orifice area, m^2
D_o	= Orifice diameter, *m*
D_c	= Cavity diameter, *m*
f	= Diaphragm's frequency, *Hz*
f_h	= Helmholtz frequency, *Hz*
h	= Orifice thickness, *m*
V	= Voltage, Volt
v	= Fluid kinematic viscosity, m^2/s

■1.0 INTRODUCTION

A synthetic jet actuator (SJA) is a device that performs periodic suction and ejection of fluid and result in a jet flow. Jet flow is a stream of fluid that mixes with surrounding medium. SJA consists of three main elements which are cavity, orifice and diaphragm. The cavity is confined by the wall with the diaphragm at the bottom and orifice as the jet exit on top. The oscillations of diaphragm control the repeating movement of the fluid from external environment into the cavity and then back to the external environment. During the injection cycle, the diaphragm moves downward result a lower pressure and thus fluid is drawn into the cavity. While in expulsion cycle, the diaphragm moves up and a high pressure condition occur in the cavity and pushes the internal fluid out through the orifice. The repetition of suction and expulsion cycles creates a shear layer which gradually formed a vortex ring at the exit of the orifice. The transmissions of vortex ring away from the orifice will result in a synthetic jet [1]. The device is known as 'synthetic' because the net change in mass through the orifice is zero [2].

SJA emerges as a flow control device which has been used to delay the separation of boundary layer on aircraft wings [3]. The technological advancement of SJA allows its application on the wings to improve the maneuverability, and decrease fuel consumption so that range and payload will be increased [4]. Intense research had been carried out in recent years to obtain the optimum operation parameters for SJA.

On the other hand, the project will use Particle-Image Velocimetry (PIV) as measurement technique. PIV is a quantitative velocity measuring technique which used small particle tracer to visualize the flow field. The velocity vector of the flow field is obtained after analysis has been done on the visualized images [5]. PIV techniques involve main process, visualisation and image analysis. There are four elements: seeding particles, camera, laser and optics and synchronizer for post processing which are the important apparatus to be considered in PIV measurement. This project was carried out to study the performance of the exit air jet velocity of a synthetic jet actuator using PIV. Air jet flow pattern of SJA to be visualized and analyzed with the assistants of particles tracer and digital images visualization.

2.0 EXPERIMENTAL SETUP

2.1 The Synthetic Jet Actuator (SJA)

The specification of SJA and its drawing is as shown below (Table 1 and Figure 1):

Table 1 Specification of SJA

Parameter	Specification
Cavity area	1268.56mm^3
Cavity volume	3805.67mm^3
Orifice type	Circular
D_o	1 mm
h	0.5 mm
Diaphragm	Murata 7BB-41-2, thickness 0.63 mm, diameter 41 mm, brass plate
Clamping medium	Araldite glue

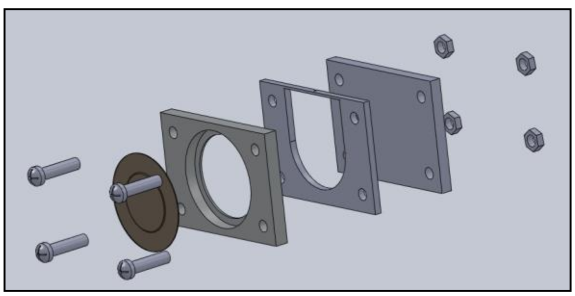


Figure 1 Drawing of SJA

2.2 PIV Experiment

To facilitate PIV measurements of SJA, the SJA was enclosed with a transparent test rig to allow for optical access and ensure the result was obtained under quiescent flow condition. The enclosed ambient air was seeded by a powder. The SJA flow was illuminated by NewWave Solo laser with a repetition rate of 8Hz. A Light sheet was generated and directly across the orifice in the x-y plane to produce a two dimensional slices of the synthetic jet. The camera system used was Flow Sense M2 (8 bit) and Dantec Dynamic Hisense system. The camera and laser were synchronized with a synchronizer. Schematic of the PIV experiment is shown as Figure 2. For a given point, 40 images were taken into a two frames per recording. The cases were investigated in this experiment are as follows:

i. Input voltage: 2V, frequency 100 to 1000 Hz with increment of 100 Hz.
ii. Frequency 250 Hz, input voltage 0.5v to 3V with increment of 0.5V.

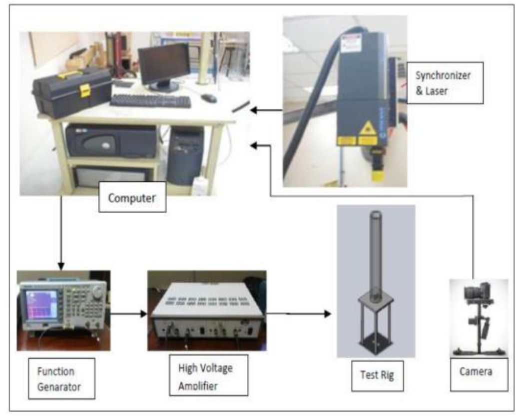


Figure 2 Schematic Photo of Experimental Set up

3.0 RESULTS AND DISCUSSION

3.1 Velocity Scalar Map

The peak velocity of the pulse jet occurred at the location within 5 mm above the orifice as shown in Figure 3 It was taken as the reference location that provides accurate and repeatable measurement for peak velocity measurement. Haniff [6] used to measure the peak velocity at 2 mm above orifice. The peak velocity point is located so near to the orifice because once the pulsed jet being push outside from the cavity, the friction from the surrounding air will reduce its momentum gradually. The energy from the pulse jet is also dissipates due to the viscosity effect of ambient air which will then form a sequence of ring vortex propagates away from the orifice. Hence, the analysis on the peak velocity will be taken on the location where 5 mm above the orifice.

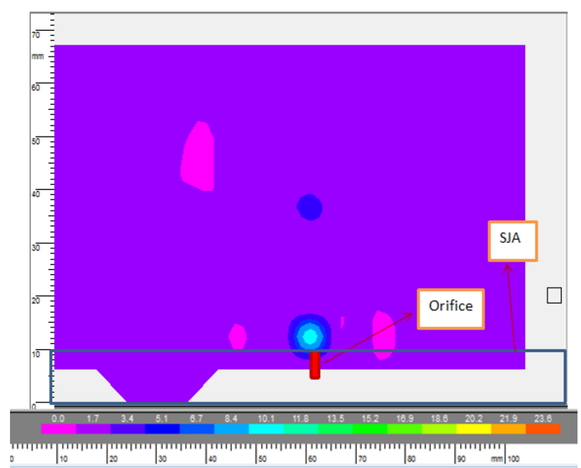


Figure 3 The peak velocity is located approximate 5 mm above the orifice

3.2 Investigation of Maximum Pulse Jet Velocity

Figure 4 shows a very close result obtained between PIV and Hot Wire Anemometer (HWA) [6]. For PIV experiment, the maximum velocity being produced achieves its peak velocity of 18.77 m/s at applied frequency 200 Hz. According to Jabbal, Tang, and Zhong [7], the containing air in the container with orifice will vibrate and creating resonance at a certain frequency if it is being disturbed.

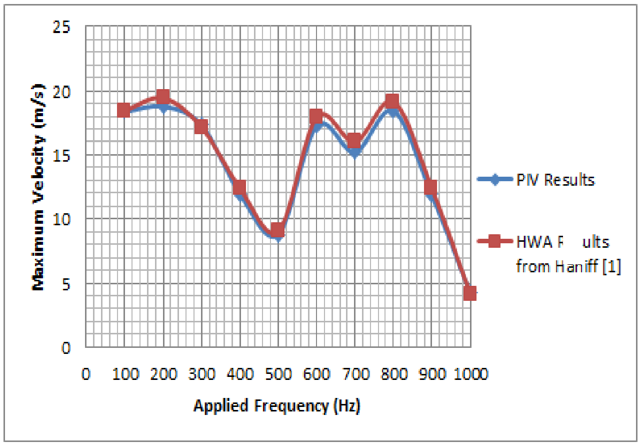


Figure 4 The maximum velocity obtain by PIV method is close to HWA results obtained from Haniff [6] at fixed voltage of 2 Volt.

This phenomenon is called Helmholtz resonance and the frequency is referred to Helmholtz frequency. The maximum pulse velocity being achieved, is believed to be caused by the Helmholtz resonance and producing a continuous source of excitation to the containing air. The small pressure difference generated by the oscillating diaphragm is being amplified by the Helmholtz frequency and produces a large mass flow through the orifice. Hence the pulse jet velocity is also increased. At 600 Hz, 700 Hz and 800 Hz do generate high pulse jet velocity. The data obtained from HWA experiment shows that, time between peak to peak pulse jet velocity for 600 Hz, 700 Hz and 800 Hz are 0.005 second, 0.010 second and 0.005 second respectively. Under the operation of these applied frequencies, the SJA takes 1.6 ms, 1.43 ms, and 1.25 ms to complete one entrainment and expulsion cycle. It is found that, at these frequencies the SJA endures 3, 7 and 4 entrainment and expulsion cycle respectively in order to accumulate enough air volume to achieve high pressure in the cavity and hence generate high pulse jet velocity. It is believe that air volume being sucked in is not pushed out entirely in the upcoming expulsion process and remain a portion of air in the cavity. The remaining volume of air inside the cavity is added with the air volume being sucked the next entrainment process. The process is repeated until the pressure inside the cavity is high enough and hence the air is expulse completely to produce a high pulse jet velocity.

As shown in Figure 5, when the applied frequency is increased, the generated vorticity are located at nearer location from the orifice. The results obtained from Jabbal, Wu and Zhong [1] show that the distance between vortex structures will decrease with higher applied frequency. The vorticity is caused by the pulse jet produced by the SJA. At higher applied frequency, the time to complete one entrainment and expulsion cycle is faster. Hence the time between the generations of pulse jet also shorter and resulted in the observed vortex structure is located nearer to the orifice in higher applied frequency.

At fixed frequency, the maximum pulse jet velocity increase from 7.53 m/s at 1.0V to its peak performance of 17.83 m/s at 2.0V as shown in Figure 6. According to the research conducted by Mossi et al [8], the displacement of diaphragm is proportional to the input voltage of the SJA. By increasing the input voltage, the displacement of the diaphragm also increases. In addition, higher deflection of diaphragm will able to entrain more air into the cavity and hence the pulse jet velocity produced also increased due to the higher pressure inside the cavity. At input voltage 2.0V, the performance of SJA is optimum as it generates the highest pulse jet velocity. However, the effect of applied frequency is also one of the key parameter for the performance of SJA as it limits the oscillating amplitude of diaphragm.

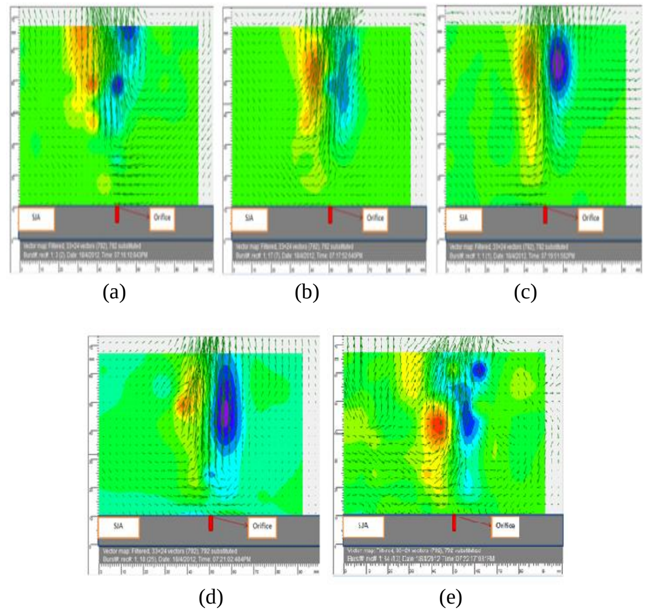


Figure 5 The location of vortex structure is moving nearer to the orifice with increment of frequency (a) 200 Hz, (b) 300 Hz, (c) 400 Hz, (d) 500 Hz, (e) 600 Hz

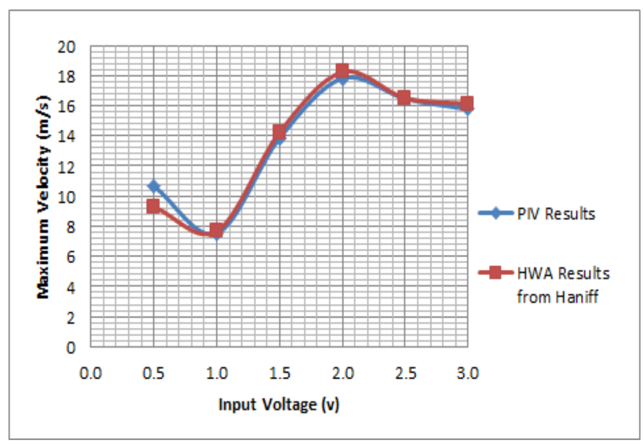
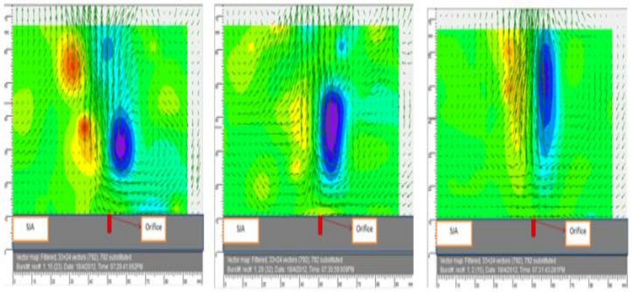


Figure 6 The result of PIV method is close to HWA results obtained from Haniff [6] at fixed frequency

Observation from Figure 7, indicate the the vorticity flow patterns being captured are becoming more stable from input voltage 1.0V to 2.0V. The flow patterns as shown in Figure 7 reveals that at fixed frequency, higher pulse jet velocity will move the vortex structure further away from the orifice. From the figure (a) 1.0V, (b) 1.5V and (c) 2.0V which have maximum pulse jet velocity of 7.53 m/s, 13.86 m/s and 17.83 m/s respectively, the vortex structure being produced is moving further away from the orifice with the increase of pulse jet velocity. According to Jabbal, Wu and Zhong [1], the vortex structure is propagating away from the orifice due to their self-induced velocity and impulse provided by diaphragm. Hence, the phenomenon can be explained that higher pulse jet velocity contain higher momentum and contribute more induced velocity and impulse to the vortex structure to move further away from the orifice.



(a) (b) (c)

Figure 7 At fixed frequency, (a) 1.0V (b) 1.5V and (c) 2.0V show that higher pulse jet velocity will move the vortex structure further away from the orifice

The result being obtained by PIV method is generally slightly lower than HWA. This can be explained as the seeding particles absorb a small portion of momentum from the pulse jet. To minimize the distortion it can be replaced by other seeding that possesses suitable diameter to provide optimum light sheet for illumination. Hence, finely dispersed oil droplets with approximate 5 microns of mean diameter are recommended.

3.3 Investigation of Maximum Vorticity

Figure 8 reveals that the maximum vorticity produced is inversely proportional to the increment of applied frequency after achieving its peak at 200 Hz. The highest vorticity of 242.5s^{-1} is found at 200 Hz, while 100 Hz produced the smallest vorticity of 112 s^{-1}. According to Jabbal, Tang and Zhong [7], the Helmholtz resonance is the cause for the increase in vortex circulation and maximum pulse velocity. Hence, at 200 Hz the effect of Helmholtz resonance is greatest for the SJA because both maximum vorticity and also maximum pulse jet velocity (refer Figure 4) are found in this operating frequency.

Besides, refer to Figure 9 (a) 300 Hz, (b) 600 Hz and (c) 900 Hz, the vorticity being capture tend to separate into primary and secondary vortex structure with the increment of frequency. We can see that when increasing the frequency the vorticity is decreasing. Explanation can be said that when there is secondary vortex appear, the strength of vorticity is reduced. Part of the vorticity created is being shared by the secondary vortex. The secondary vortex is affecting the vorticity strength.

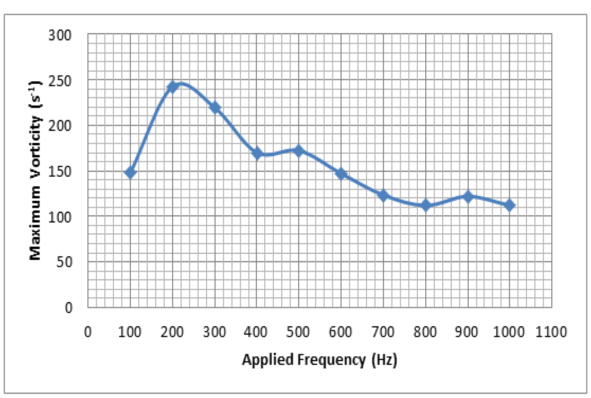
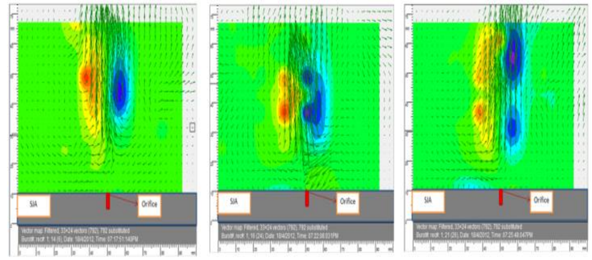


Figure 8 The maximum vorticity produced is inversely proportional to the increment of applied frequency



(a) (b) (c)

Figure 9 The strength of vorticity is lower when there is occurrence of secondary vortex as shown (a) 300 Hz, (b) 600 Hz, (c) 900 Hz

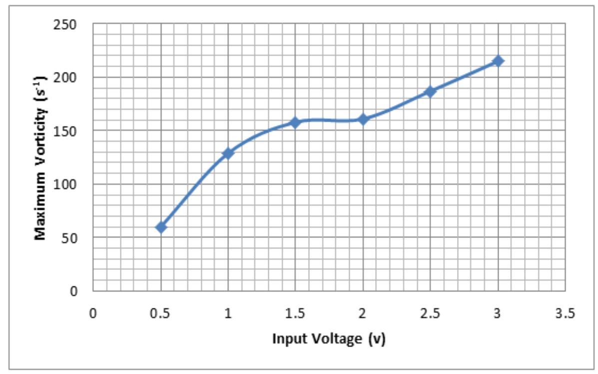


Figure 10 The maximum vorticity generated is proportional to the input voltage at fixed applied frequency of 250 Hz

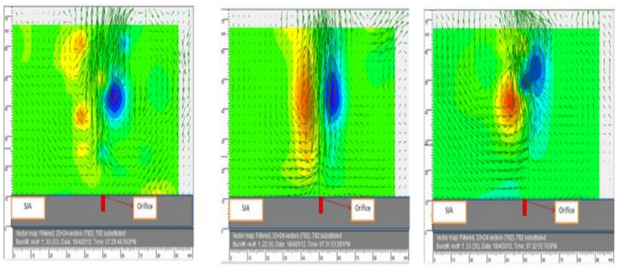
The maximum vorticity generated by the SJA is proportional to the input voltage at fixed operating frequency of 250 Hz as shown in Figure 10. At input voltage of 0.5V, it gives the lowest vorticity among other input voltage which is 60s^{-1}. The strength of vorticity increases with the increment of input voltage and the maximum vorticity of 215s^{-1} is achieved at 3.0V. Jabbal, Wu and Zhong [1] said that an approximation of the total circulation can be obtained by:

$$\Gamma_0 \approx \int_0^{T/2} \frac{u_0^2(t)}{2} dt = \frac{\pi^2}{128} \Delta^2 f \left(\frac{D_c}{D_0}\right)^4 \quad (1)$$

The total circulation generated is a function of displacement of diaphragm, applied frequency and cavity's diameter as well as orifice's diameter. The displacement of diaphragm is proportional to input voltage as mentioned by Mossi, et al [8]. In the condition that other components such as applied frequency, diameter of cavity and orifice are constant, therefore the increment of input voltage means the increase in diaphragm's deflection and resulting in the increase in total circulation hence the strength of vorticity also increased.

However, the circulation's equation 1 as suggested by Jabbal, Wu and Zhong [1] is not applicable for the case study where fixed input voltage. This is because the frequency has limited the amplitude of diaphragm's deflection. Therefore the vorticity is decreasing with the increment of applied frequency in the experiment of fixed input voltage as shown in Figure 8.

Figure 11 shows the vorticity being capture at input voltage (a) 1.0V, (b) 2.0V and (c) 2.5V. The primary vortex and secondary vortex is becoming nearer with the increment of input voltage. And the strength of vorticity is increasing when the secondary is near to the primary vortex. The similar finding is being found in the investigation with fixed input voltage as shown in Figure 9 where the strength of vorticity is being reduced with the occurrence of secondary vortex. Besides, the higher vorticity will show a flow pattern of smaller vortex structure as shown in Figure 11 (c).



(a) (b) (c)

Figure 11 At (a) 1.0 V, (b) 2.0 V and (c) 2.5 V, strength of vorticity is higher when there is no secondary vortex

■4.0 CONCLUSION

The experimental PIV method had successfully implemented on the study of jet flow velocity for SJA. Besides, the post processing analysis with Flowmanager software had been done on the PIV raw data to extract information on the jet flow velocity and flow pattern. These results from PIV experiment were compared to previous researches. Further explanations had been done to describe the behavior of SJA. Several conclusions can be drawn based upon the foregoing analysis.

1. PIV experiment provides a whole field velocity vector map showing that location of 5mm above the orifice is the optimum location that provides accurate and repeatable measurement for the investigation of maximum pulse jet velocity.
2. At fixed input voltage, the flow pattern of vortex structure formation is affected by the applied frequency. While at fixed applied frequency, the formation of vortex structure is mainly affected by the pulse jet velocity.
3. For the investigation of maximum pulse jet velocity and vorticity at fixed input voltage with oscillating frequency varies, maximum pulse jet velocity of 18.77 m/s and vorticity of 242.5s^{-1} are produced at applied frequency 200 Hz which is believed to be affected by the Helmholtz resonance effect.
4. In investigating the maximum pulse jet velocity and vorticity at fixed oscillating frequency with input voltage varies, maximum pulse jet velocity of 17.83 m/s was produced at input voltage of 2.0V while maximum vorticity was found at input voltage of 3.0V due to the highest deflection of the diaphragm to entrain a large amount of air into the cavity.

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